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August 25, 2015

Ms. Marlene H. Dortch
Secretary
Federal Communications Commission
445 12th Street, S.W.
Washington, D.C. 20554

**Re: *Ex parte* presentation in IB Docket No. 12-340; IBFS File Nos. SAT-MOD-20101118-00239; SAT-MOD-20120928-00160; SAT-MOD-20120928-00161; SES-MOD-20121001-00872**

Dear Ms. Dortch:

Attached please find the final GPS Sensitivity Measurement Plan prepared by Roberson & Associates, a consultant to Covington & Burling LLP in connection with our representation of LightSquared. A presentation summarizing the test plan is also attached. Preliminary details and updates regarding this test plan have been reported to the Commission in previous filings, including most recently in an *ex parte* letter submitted by the undersigned on July 15, 2015.

We are pleased to inform the Commission that testing is already underway. We look forward to sharing the test results with the Commission and other stakeholders upon completion.

Please direct any questions to the undersigned.

Respectfully submitted,

Gerard J. Waldron

Gerard J. Waldron
*Counsel to LightSquared*

Attachments

Roberson and Associates, LLC

Technology and Management Consultants

# GPS SENSITIVITY MEASUREMENT PLAN

AUG 24, 2015

V1.1

# 1 MEASUREMENT PLAN EXECUTIVE SUMMARY

## 1.1 Purpose

The purpose of the GPS receiver measurement project is to collect supporting data to establish the impact on Key Performance Indicators (KPIs) that a GPS device user may experience when L-band LTE downlink and uplink signals are present. Signal to noise ratios in the form of reported C/No values and other GPS receiver data will also be collected. Emphasis is on real world expected LTE signal levels including temporal and spatial variations in signal levels.

## 1.2 Deliverables

For each device in each category the main deliverables are detailed records of the KPI statistics observed as a function of LTE signal levels at the input to the GPS device. A determination is made of the received power adjacent band levels versus observed changes in KPI statistics without any pass/fail determination.

# 2 KPI MEASUREMENT PLAN

## 2.1 Test Plan for Cellular GPS Devices

Cellular GPS devices will be tested as per the TWG devised test plans for Accuracy [TWG Report, Sections 3.2.9.2.2 and 3.2.9.2.3] and Sensitivity [TWG Report, Section 3.2.9.2.1]. If it is infeasible to perform the tests exactly as per these test plans, the latter may be modified in the future. These 3GPP tests are found in 3GPP Specification 37.571-1 for UTRAN and E-UTRAN based systems. The Sensitivity test is described in section 7.1 and the Accuracy test is described in section 7.2.

The two figures below are taken from TS 37-571-1.

**Table 7.1.1.2: Requirements Sensitivity Coarse time assistance**

| Success rate | 2-D position error | Max response time |
|---|---|---|
| 95 % | 100 m | 20 s |

**Table 7.1.1.3: Parameters Sensitivity Coarse time assistance - Sub-Test 1**

| Parameters | Unit | Value |
|---|---|---|
| Number of generated satellites | - | 8 |
| HDOP Range | - | 1.1 to 1.6 |
| Propagation conditions | - | AWGN |
| GPS Coarse time assistance error range | seconds | ±2 |
| GPS L1 C/A Signal for one satellites | dBm | -142 |
| GPS L1 C/A Signal for remaining satellites | dBm | -147 |

Figure 1 3GPP Sensitivity KPI and test conditions from TS 37.571-1

**Table 7.2.2: Requirements Nominal Accuracy - Sub-Test 1**

| Success rate | 2-D position error | Max response time |
|---|---|---|
| 95 % | 30 m | 20 s |

**Table 7.2.4: Parameters Nominal Accuracy - Sub-Test 1**

| Parameters | Unit | Value |
|---|---|---|
| Number of generated satellites | - | 8 |
| HDOP Range | - | 1.1 to 1.6 |
| Propagation conditions | - | AWGN |
| GPS Coarse Time assistance error range | seconds | ±2 |
| GPS L1 C/A Signal for all satellites | dBm | -130 |

Figure 2 3GPP Accuracy KPI and test setup from TS 37.571-1

## 2.2 Key Performance Indicators (KPIs) for non-Cellular GPS Devices

The table below lists a preliminary list of the KPIs of the different GPS device classes. This list is subject to enhancement as additional inputs are received hopefully including inputs from the key GPS vendors whose devices will be the subject of this test. Dilution of Precision (DOP) is a function of the position of satellites and not a KPI dependent on LTE signals level. Since C/No is reported in NMEA messages along with other data it will be collected.

C/No and the number of satellites are reported for each satellite in NMEA messages and will also be collected and included in the statistical analysis. Not all devices report C/No.

Table 1 KPIs for GPS device category

| | Cert Aviation | Aviation (Uncert.) | High Precision | Timing | Cellular | General Nav |
|---|---|---|---|---|---|---|
| **KPI** | 3D Position Error<br>• See 3.2.3 below | • 3D Position Error<br>• | • 3D Position Error<br>• Loss of RTK | • Timing Error<br>• | • 3GPP KPIs<br>• 2D Position Error<br>• | • 2D Position Error<br>• |
| **System Data** | • C/No | • Satellites in view<br>• C/No<br>• DOP<br>• | • Augmentation Signal Quality<br>• Satellites in view<br>• C/No<br>• DOP | • Frequency Error<br>• Satellites in view<br>• C/No<br>• DOP | • Satellites in view<br>• C/No<br>• DOP<br>• | • Satellites in view<br>• C/No<br>• DOP<br>• |

## 2.3 GPS Device List

The list of GPS devices to be tested is listed below. Two devices which were tested in 2011 are labeled. A Javad device may also be added as a reference for comparison with the other high precision GPS receivers.

| **Aviation (certified)** |
|---|
| Garmin GTN 625 |
| Avidyne IFD 440 |
| **Aviation (non-certified)** |
| Garmin GPSMAP 696 |
| Garmin aera 510 |
| **General location and navigation** |
| Garmin Nuvi 2597LMT |
| Garmin Nuvi 55LM |
| TomTom VIA 1515M |
| Alpine In-Dash X008U |
| Garmin GPSMAP 76 CSx (tested in 2011) |
| Garmin eTrex H (tested in 2011) |
| Garmin Nuvi 2495LMT |
| TomTom Go 50S/60S |
| Garmin/Panasonic Uconnect 8.4N RB5 |
| Motorola APX 7000 |
| Motorola MW810 |
| Pioneer AVIC-5100NEX |
| Harman Toyota Entune 86140-02050 |
| Bosch in-dash Nissan 25915CJ0A |
| Garmin GPSMAP 78 SC |

| |
|---|
| Garmin Montana 650t |
| Magellan Explorist 350H |
| Bushnell Onix 400 Waterproof Hiking GPS |
| Furuno GP32 |
| Wabtek Navigation Sensor Module |
| **Cellular** |
| Apple iPhone 5s |
| Apple iPhone 6 |
| Samsung Galaxy S5 |
| Samsung Galaxy S6 |
| iPad (w/cellular data) |
| Samsung Galaxy Tab 4G LTE |
| **High precision** |
| Deere Starfire 3000 (0907PC, 1010, 2010 and 7800) |
| NovAtel Smart6 or Smart6-L |
| Topcon SGR-1 |
| Topcon System 310 |
| Trimble AgGPS 542 |
| NAVCOM SF-3050 |
| Trimble Geo 7x |
| Trimble TM3000 |
| Trimble SPS855 GNSS Receiver |
| Trimble SPS985 Antenna |
| Trimble Net R9 or R8s Base RTK for R8s rover |
| Trimble R8s |
| Topcon HiPer V |
| **Timing** |
| Arbiter 1088B GPS Satellite Clock (40ns) |
| Symmetricom 1510-602 |

## 2.4 Antennas

Listed below are some antennas that are resilient to adjacent channel signals.

| Vendor | Class | Model |
|---|---|---|
| AeroAntenna Technology | Aviation | AeroAntenna AT575-93 |
| PCTel | Mobile | 3915D-HR |

| | | |
|---|---|---|
| PCTel | Mobile | 8171D-HR |
| PCTel | Timing | GPS-TMG-HR-26N |
| JAVAD (LSQ Provided) | High Precision | N/A |
| Novatel | High Precision | GPS-713-GGG-N |

## 2.5 Conducted Measurements

The diagram below shows the basic elements of a conducted test. Conducted testing will be used in the development of data collection software, to narrow down the range of LTE levels used in testing, and to determine the length of time (labeled TRECORD below) needed to collect KPI statistics. GPS and LTE signals are generated and applied with attention paid to not increasing the noise floor at the receiver. Intermodulation distortion at the generator outputs caused by reflected power must be prevented. This diagram includes elements that may not be used in all tests. The Precision Correction source is the augmentation signal source that may be used with high precision GPS receivers. In assisted mode, GPS cell phones use information provided by the network to speed up Time To First Fix (TTFF) by providing time and satellite information to the phone. Assisted GPS also improves indoor performance by improving sensitivity.

The computer on the right represents the KPI data collection.

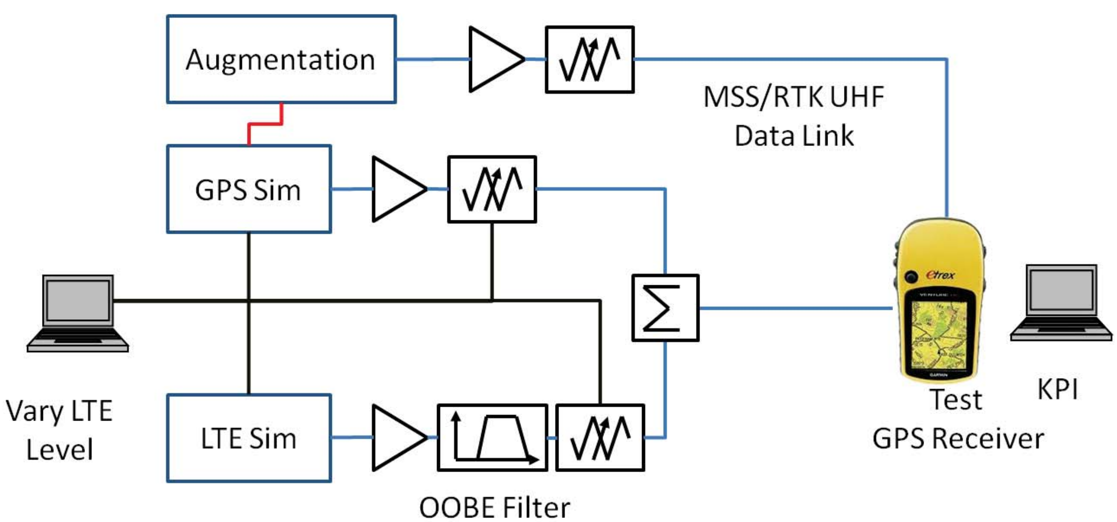



Figure 3 Simplified GPS KPI measurement schematic

## 2.6 Radiated Measurements

For GPS devices where conducted tests are not feasible or not deemed appropriate radiated tests will need to be performed. The test sequences will be the same. The most significant difference is that both the GPS and LTE signal levels will have to be amplified significantly to compensate for the propagation losses in an anechoic chamber. The first diagram below shows the basic schematic of the radiated tests. A computer shown on the left controls the signal frequencies and levels while the computer on the right records the desired KPI information. Not shown is the means for determining the LTE level at the GPS receiver. There are active antennas which include bandpass filtering that may be comparison tested. The LTE signals need to be amplified significantly to be able to apply up to -20 dBm LTE power at the GPS receiver. Both the free space path loss in the chamber and the high peak to average ratio of the LTE waveform need to be considered in the choice of amplifier.

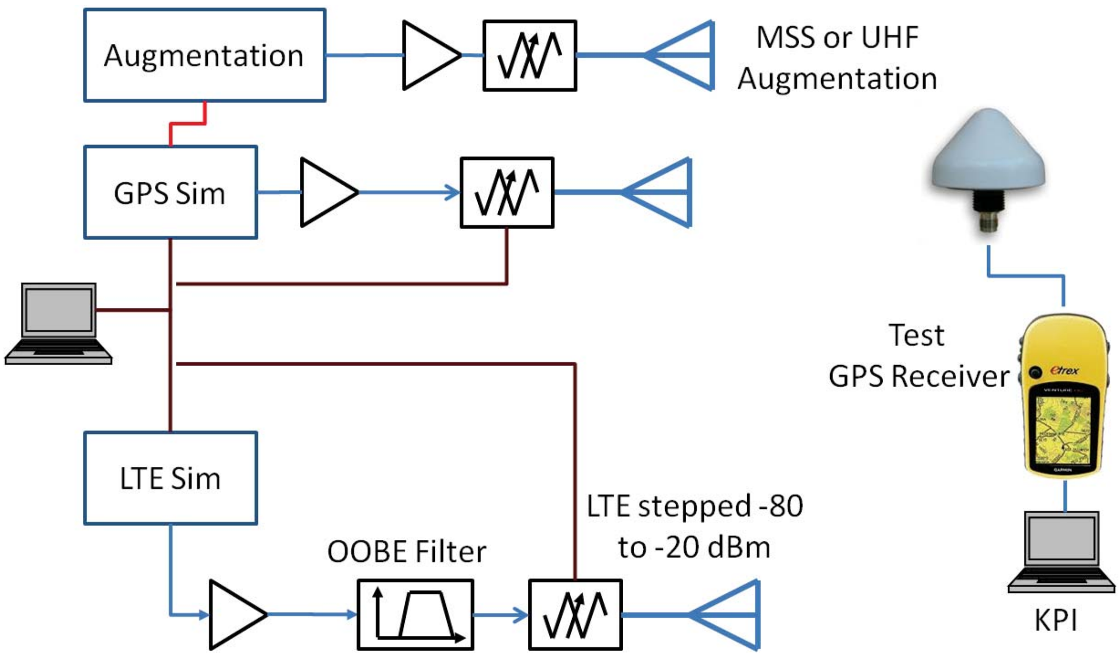



Figure 4 Simplified radiated GPS KPI measurement schematic

Knowledge of GPS receiver antenna gain patterns (azimuth, elevation, and polarization) will be required to project the received power levels back to emitter antennas in use case analyses. To avoid taking radiated measurements at multiple incidence angles on the antenna, devices will be tested at one angle measured in the laboratory, and, in the use case analyses, adjusted for the angles of arrival called for by specific use cases. 3D antenna pattern data from the equipment manufacturers will be required for this purpose, absent which, realistic assumptions will be made. Note that the laboratory set up will <u>not</u> try to emulate the actual angles of arrival of the LTE and GPS signals – they will be set up with convenient angles of arrival that produce strong responses from the GPS antenna. Note also that the GPS signals from different satellites will be combined and radiated as one composite signal towards the GPS receiver, most likely with an angle of arrival corresponding to the antenna's boresight. The LTE signal will likewise be radiated with an angle of arrival within +/- $45^0$ of boresight. In the use case analyses, the received powers of LTE signals will be adjusted by the difference in an antenna gain between the angle of arrival used in the laboratory and that called for by a specific use case.

## 2.7 Dependencies and Assumptions

Only the 10 MHz bandwidth version of LTE signals will be used in the measurements. Downlink LTE signals will be assumed to be supporting many devices and have most or all LTE resource blocks assigned.

Uplink LTE signals will be representative of high data rate, greater than 1Mbps, traffic, for example traffic representative of streaming video, nominally 3.5 Mbps. The high data rate case is the worst case since this represents transmitting on the most time and frequency resource blocks over time. Lower uplink data rates may be measured also but with a lower priority. Lower data rates will be experienced in the field and result in lower radiated power, since many of the resource blocks are not being used.

The post measurement Analysis of the data involves comparison of the measured received estimated positions (for navigation receivers) and time (for timing receivers) with the true values. The basic process is to compare true position and time with received values. 2D and 3D mean and RMS position errors and timing errors will be calculated and C/No values recorded as functions of LTE downlink and uplink signal levels at the receiver. No pass/fail judgment will be made, but analysis will be performed to estimate the impact to the user of KPI degradation in real life scenarios.

### 2.7.1 LTE Bands

The bands for the LTE signals to be used in the KPI measurements are shown below: Only 10 MHz bandwidths will be used. Uplink signals will include LTE resource block scheduling effects for high (3.5 Mbit/second) data rate file transfers..

| LTE Direction | LTE Band |
|---|---|
| Downlink | 1526-1536 MHz |
| Downlink | 1545-1555 (Schedule permitting) |
| Downlink | 1670-1680 |
| Uplink | 1627.5-1637.5 |
| Uplink | 1646.7-1656.7 |

### 2.7.2 LTE Uplink Signal Generation OOBE Noise Floor

The uplink LTE signals need to simulate the entire output power spectrum that is expected to be seen from a cellular phone. The OOBE limit for LightSquared's devices is -95 dBW/MHz in the Radio Navigation Satellite Service band (1559-1610 MHz). The tests will emulate LightSquared devices emitting OOBE at their licensed limit. The diagram below shows the desired power spectral density for LTE uplink signals.

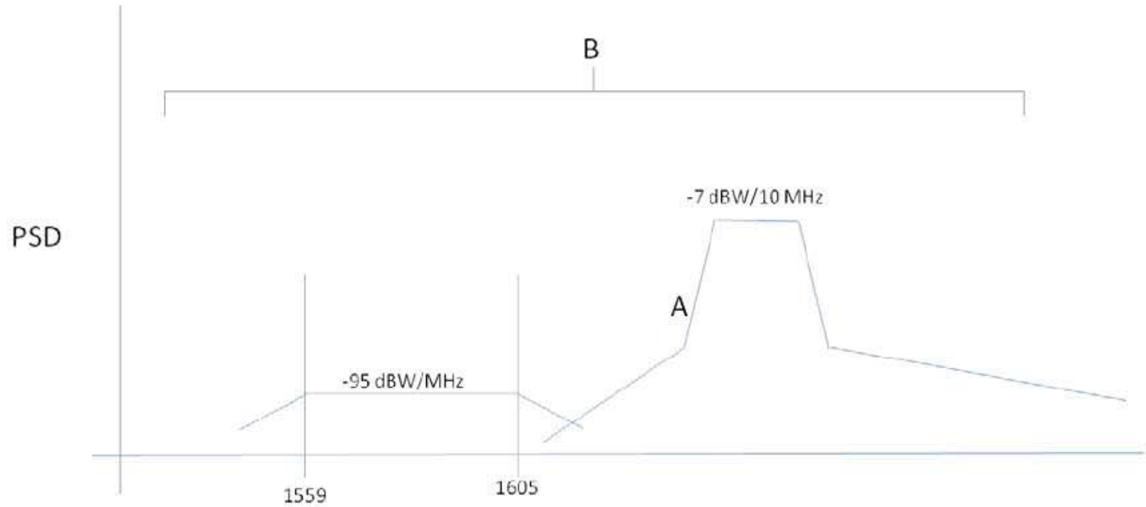



Figure 5 LTE Uplink Power Spectral Density

The LTE uplink has a maximum power of +23 dBm over a 10 MHz bandwidth. The noise floor should not exceed -95 dBW/MHz. These are EIRP values.

The schematic below shows one possible implementation for an LTE uplink with a specific OOBE noise floor. The schematic shows a wideband white noise generator output combined with the LTE uplink signal to produce a test signal with the power spectral density shown above. The actual performance of the OOBE filter will influence the need for the additive white noise source.

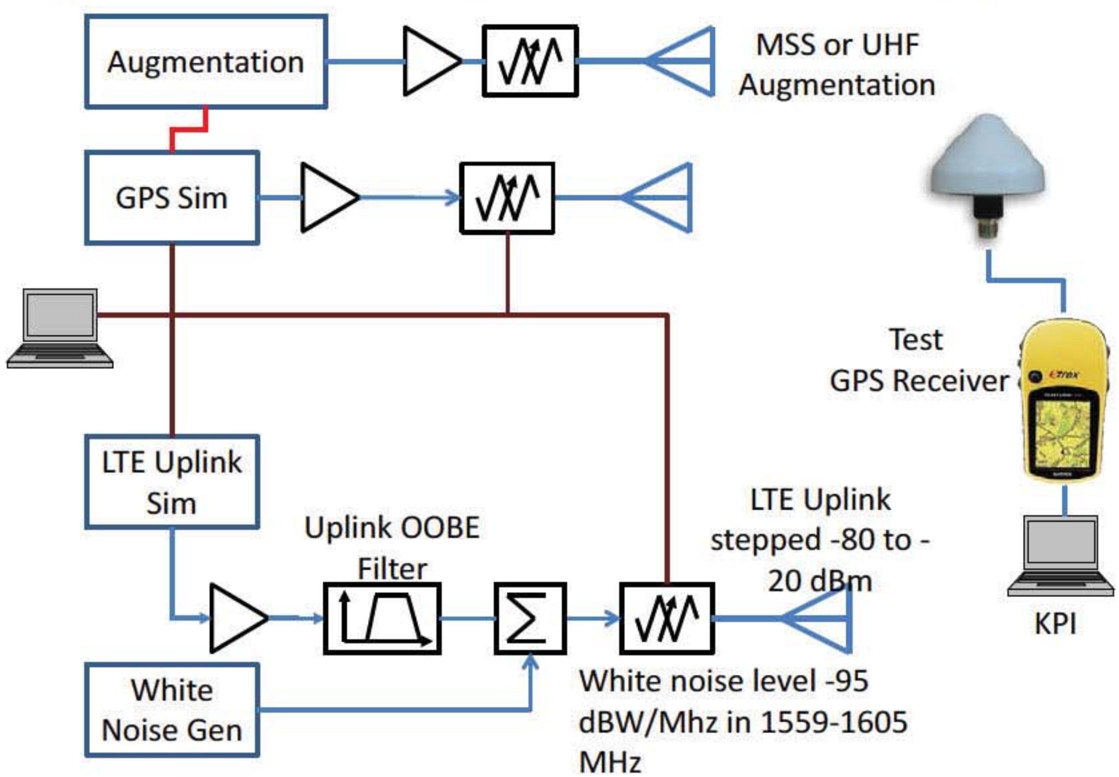



Figure 6 Schematic for producing LTE uplink OOBE noise at -95 dBm/MHz

### 2.7.3 GPS Conditions

Two GPS conditions will be provided for some KPI measurements.

| Condition | Number | Level |
|---|---|---|
| Open | 8+ satellites | -130 dBm |
| Stressed | 5 Satellites | TBD |

### 2.7.4 GPS Impairments

Other GPS system impairments, external to the receiver, will be emulated where feasible. These impaired conditions are summarized in the table below. These are important to be able to accurately gauge the incremental impact of LTE signals. These impairments were derived starting with values from "GLOBAL Positioning System Standard Positioning Service Performance Standard" 4th Edition, From GPS DIRECTORATE; Page 65 and 108. A conservative Zero Age of DATA (AOD) was used. Finally, the 95 % values were converted to 50% CEP values.

**Table 2GPS impairments**

| | zero AOD, 95% Error | CEP50 (values used) |
|---|---|---|
| Group Delay Stability | 3.1 | 1.4911 |
| Other Space Segment Errors | 1 | 0.481 |
| Clock/Ephemeris Estimation | 2 | 0.962 |
| Clock/Ephemeris Curve | 0.8 | 0.3848 |
| Ionospheric Delay | 9.8 - 19.6 (14.7) | 7.0707 |
| Group Delay Time | 4.5 | 2.1645 |
| Other Control Segment Errors | 1 | 0.481 |
| Tropospheric Delay | 3.9 | 1.8759 |
| Receiver Noise | 2.9 | 1.3949 |
| Multipath | 0.2 | 0.0962 |
| Other User Segment Errors | 1 | 0.481 |
| 95% System UERE | 12.7 - 21.2 (16.65) | |
| CEP50 | | 8.009047212 |

## 2.8 Equipment List

The list below includes the equipment that may be needed for measuring the sensitivity of GPS KPIs to LTE signal levels

1. Spirent or other GPS Test Set capable of introducing typical GPS impairments
2. MSS Augmentation signal source
3. RTK Augmentation message generation and RF, WiFi, or Ethernet RTK signal source
4. LTE Signal Generator
5. RF Amplifiers
6. RF Attenuators
7. RF Signal Combiners

8. LTE TX OOBE Filters
9. LTE TX and GPS TX Antennas
10. GPS RX Antennas
11. GPS RX Filters
12. Timing jitter test equipment
13. Frequency Error test equipment

## 2.9 Calibration and Pretest

Prior to collecting detailed KPI data the devices need to be characterized for their basic performance levels. The GPS devices need to have their GPS signal sensitivities measured and recorded. This involves applying a GPS constellation signal at a fixed, known level to each device and recording the reported C/No for each device. No adjacent band signal will be present during these measurements.

In addition to sensitivity ($C/N_0$ reported with -130 dBm received signal level) the ***gradient*** of the reported $C/N_0$ vis a vis input $C/N_0$ will also be measured. The value of the received signal level will be reduced in 1 dB steps from -130 dBm to -145 dBm and the reported $C/N_0$ reported for each step. Ideally a given reduction in the input signal level should result in an identical reduction of $C/N_0$ but this may not be the case with actual receivers.

A large variation in C/No or its gradient between GPS devices will need further investigation and a decision will be made regarding continuing measurements with that device.

Prior to data collection it is important to verify that the thermal noise floor has not been increased and that no spurious intermodulation signal produced by interactions between the GPS and LTE signal generators.

### 2.9.1 Pretest GPS Impairments

There are two pretest GPS conditions of interest. These are the un-impaired OPEN and impaired OPEN GPS conditions. These tests can also be performed during step 2 shown in the LTE sensitivity test sequence shown in Figure 7 below.

| GPS Impairment | GPS Condition | KPIs/Network Data |
|---|---|---|
| Un-impaired | OPEN | Described in Table 1 |
| Impaired, Table 2 | OPEN | Described in Table 1 |

# 3 KPI MEASUREMENT

## 3.1 Measurement Sequence

The basic sequence to measure the changes in KPIs as a function of LTE signal level is shown below. The idea is to apply LTE signal and increase the level in 1 dB steps and capturing statistically valid KPI data sets at each step. A baseline set of KPI data without the LTE signal will also be collected.

The GPS simulator will be set to emulate standard User Equivalent Range Errors (UERE)) that are independent of receiver C/$N_0$. The error sources will include at least: satellite ephemeris error, satellite clock error, ionospheric and tropospheric delay error and standard multipath profiles (conforming to a standard such as 3GPP). Receivers using augmentation signals may be able to remove a large part of these errors but non-augmented receives will experience a baseline rms error, as they do in real life operation, that will be present in the absence of LTE signals. The KPI statistics will show the impact of the LTE signals on the baseline error.

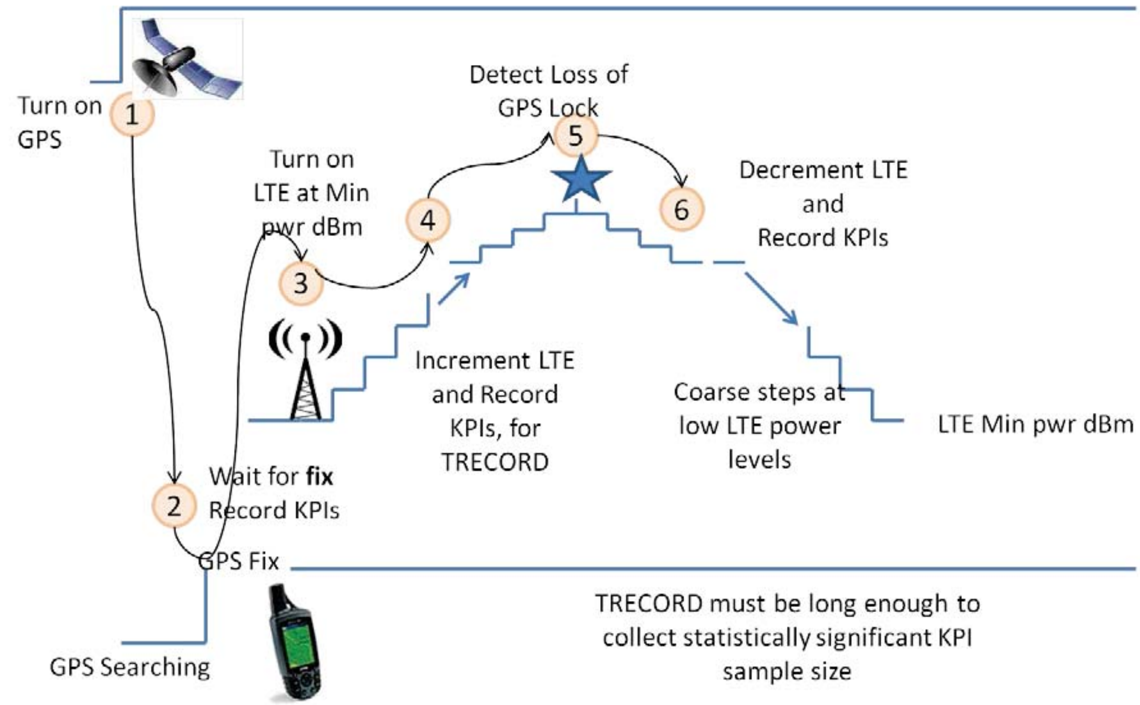



Figure 7 Generic GPS KPI measurement sequence

The pseudo-code description for the MEASURE_KPI_SET() sequence is given below. The parameter TRECORD must be long enough to capture a large enough set of KPI measurements so that statistically valid KPI averages and standard deviations can be calculated. TRECORD may be as long as one minute or more for devices that report KPI values at a low rate.

```
Power GPS device
  Apply GPS signal
  Wait for the GPS receiver to enter the fix-found state
  Adjust GPS source level until received GPS SNR (C/No) is 45
        dB.Hz
  Record baseline GPS NMEA signal parameters, and KPI values for
        TRECORD seconds.
  Apply LTE signal
  Adjust the LTE level until the received LTE signal level is -85
        dBm.
  Loop until LTE level reaches -20 dBm
    record GPS NMEA signal parameters and KPI values for TRECORD
        seconds.
```

```
    increase LTE level by (coarse 5 dB then fine 1 dB)
  Loop until LTE level reaches -80 dBm
     record GPS NMEA signal parameters and KPI values for TRECORD
        seconds.
     decrease LTE level by (fine 1 dB then coarse 5 dB)
```

## 3.2 Aviation Certified Measurements

### 3.2.1 Aviation Certified situation

Certified aviation GPS receivers have to meet RTCA standards for immunity to adjacent band signals. It is important to understand how the ability of certified aviation receivers to accurately report 3-D position is affected by the presence of LTE signals in the adjacent band.

### 3.2.2 Desired Goals

Characterize the 3D position error performance of a small sample of certified aviation devices as a function of a constant LTE signal at different levels. The change in position error will be used as the KPI, and compared to the measurement of 1 dB C/No reported by the device.

### 3.2.3 Plan

Measure only a small number of certified aviation GPS receivers. Standard RTCA tests are very involved and include C/No as a performance metric so C/No needs to be collected along with 3D position error to be able to show that the GPS receivers meet and exceed the RTCA standards.

Aviation devices will not be subject to urban canyon effects. The Stressed GPS conditions do not apply.

### 3.2.4 Assumptions

Access is available to NMEA messages or C/No data.

### 3.2.5 Test Sequence

The pseudo-code for static measurements is given below

```
Set GPS condition to OPEN
For each downlink frequency band (1531, 1550, 1675)
    MEASURE_KPI_SET()
For each uplink frequency band (1631, 1657)
    MEASURE_KPI_SET()
Calculate KPI averages and standard deviations for each LTE level
```

## 3.3 Aviation (uncertified) Measurements

### 3.3.1 Aviation (uncertified) situation

Uncertified aviation devices offer a wealth of information to pilots. GPS receiver data is linked to maps, terrain databases, and airport databases. Cellular devices are very widely used and it is likely they will operate in close proximity to aviation devices while a plane is on the ground. Uplink signal levels corresponding to those that might be seen for distances as close as a few meters need to be tested.

Airplanes are also able to view multiple base-stations when in the air at cruising altitudes. Testing with downlink signals is an important consideration at lower altitudes during takeoff and landing.

### 3.3.2 Desired Goals

Characterize the KPI performance of the latest uncertified aviation devices as a function of a constant LTE signal at different levels.

### 3.3.3 Plan

Measure only the high sales volume devices (listed in device table) and capture and store KPI data as function of LTE signal strength. Independent of market share, include a few devices known/expected to have best in class tolerance to adjacent band power levels. Log true position, and other KPI data from simulator. Plot RMS KPI errors in KPI values vs. LTE signal level and C/No. Aviation devices will not be subject to urban canyon effects. The Stressed GPS conditions do not apply.

Analysis: Compare true position and velocity with received values. Plot absolute and RMS errors of KPIs.

### 3.3.4 Assumptions

Access is available to 3D location error data and NMEA data.

### 3.3.5 Test Sequence

The pseudo-code for static measurements is given below

```
Set GPS condition to OPEN
For each downlink frequency band (1531, 1550, 1675)
    MEASURE_KPI_SET()
For each uplink frequency band (1631, 1657)
    MEASURE_KPI_SET()
Calculate KPI averages and standard deviations for each LTE level
```

## 3.4 High Precision Measurements

### 3.4.1 Situation: High Precision Location

High Precision GPS receivers may have wider RF front end bandwidths than other GPS devices. This is because they need to resolve the ambiguity in carrier phase to achieve centimeter accuracy.

Some also use augmentation signals in the adjacent 1525-1559 MHz MSS band and share the RF front end circuitry between the MSS augmentation signal receiver and the GPS receiver. Others use augmentation signals in the UHF and other bands.

Solutions have been proposed and some demonstrated to allow LTE operation in the L-band.

### 3.4.2 Goals

First, determine if GPS device performance has improved since 2011. Characterize the performance of the newer high sales volume high precision devices to update the performance baseline.

Second, determine if high immunity antennas are a viable technique to improve interoperability. Test and compare the performance of high precision receivers which use antennas which limit the receive bandwidth to the GNSS band.

### 3.4.3 Plan

Measure representative high precision GPS receivers, capture and store KPI data as a function of LTE signal strength.

Repeat the measurement with a high interference immunity antenna.

### 3.4.4 Analysis:

Compare true position with received values. Plot RMS 3D location errors vs. LTE signal levels for each test frequency with and without high immunity antennas present. Plot availability of augmentation signal vs. signal level.

### 3.4.5 Assumptions

MSS augmentation signals and RTK augmentation signals can be generated and supplied to the GPS device under test.

Access is available to 3D location error data.

### 3.4.6 Measurement Test Sequence

Pseudo-code for static measurement of high performance GPS receivers is given below

```
For each downlink frequency band (1531, 1550, 1675)
  For each GPS condition (Open, stressed)
    MEASURE_KPI_SET()
For each uplink frequency band (1631, 1657)
```

```
  For each GPS condition (Open, stressed)
    MEASURE_KPI_SET()

Enable MSS Augmentation Signal
For each downlink frequency band (1531, 1550, 1675)
  For each GPS condition (Open, stressed)
    MEASURE_KPI_SET()
For each uplink frequency band (1631, 1657)
  For each GPS condition (Open, stressed)
    MEASURE_KPI_SET()

Enable RTK Augmentation Signal
For each downlink frequency band (1531, 1550, 1675)
  For each GPS condition (Open, stressed)
    MEASURE_KPI_SET()
For each uplink frequency band (1631, 1657)
  For each GPS condition (Open, stressed)
    MEASURE_KPI_SET()
Calculate KPI averages and standard deviations for each LTE level
```

### 3.4.7 Potential Issues: Augmentation Signals

Certain augmentation signals will likely require cooperation from the manufacturers. GPS signal constellation generators may be able to produce some augmentations signals. Providing an augmentation signal may require a second base unit in addition to the unit being tested.

### 3.4.8 MSS Augmentation Signal

If a proprietary source of MSS augmentation signal cannot be obtained and installed in time then an alternative is to use available commercial MSS augmentation signals. The schematic below shows how an external antenna can be used to gather GPS and MSS augmentation signals and apply them to a GPS receiver under test in an anechoic chamber. Without a location reference from a GPS signal generator the "true" location will have to be estimated from a long term average under LTE signal "Off" conditions.

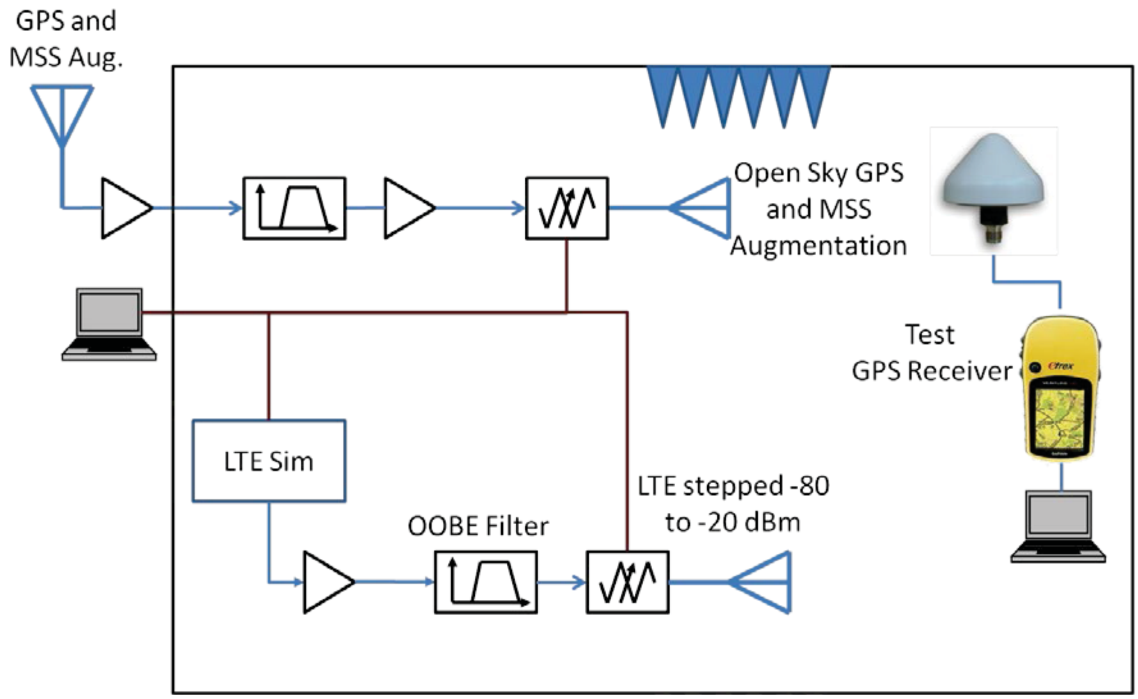



**Figure 8 External GPS plus MSS augmentation signal capture**

### *3.4.9 RTK Augmentation Signal*

Commercial and public RTK correction data is available from many sources. There are statewide networks and commercial networks that make RTK correction data available over cellular internet connections. The schematic below shows a system for gathering commercial cellular RTK correction data from a cellular or other wireless data network for application to the GPS receiver under test. Note the RTK antenna on the GPS receiver.

An alternative would be to use commercial internet based RTK services if possible.

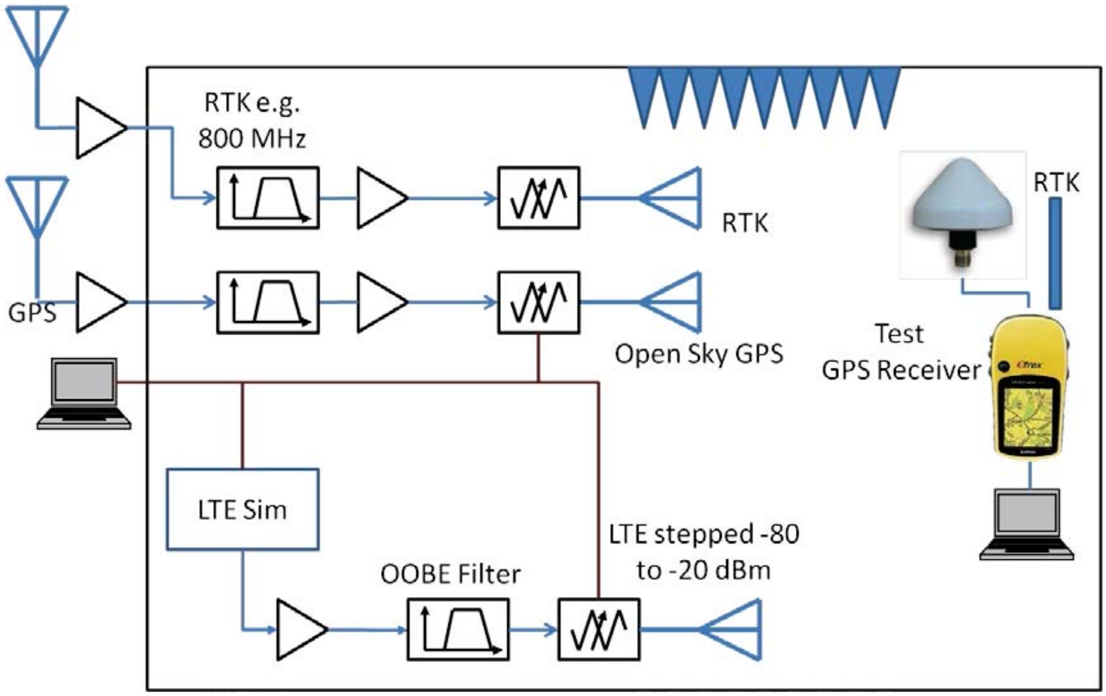



Figure 9 Insertion of commercial RTK into test chamber

## 3.5 Timing

### 3.5.1 Situation: High Precision Timing

Timing GPS receivers are used to maintain synchronization among widely distributed network elements, communication system endpoints, power generation, and other types of infrastructure. Timing receivers performed well in earlier testing.

Timing receivers generate timing and frequency reference signals using data from the received GPS satellite signals. Common outputs include a 1 PPS (pulse per second) pulse signal and a 10 MHz frequency reference.

There are antennas that are marketed as resilient. The differences in KPI performance levels seen when resilient and standard antennas are used may be compared.

In practice, Timing Receivers are fixed and carefully positioned such that the stressed GPS condition is not applicable.

### 3.5.2 Goals

Show that GPS Timing receivers continue to be relatively immune to adjacent band signals.

Show that timing GPS device performance has improved since 2011.

Determine if resilient antennas are superior to standard antennas.

### 3.5.3 Plan

Measure representative high precision timing GPS receivers and capture and store KPI data as function of LTE signal strength.

Analysis: Compare true KPI timing values with received values. Plot mean and RMS timing errors vs. signal levels for each test frequency.

The measurements may be repeated with narrow bandwidth high immunity antennas.

### 3.5.4 Assumptions

- Access to the precise 1 pps (pulse per second) output from the GPS constellation generator is available to compare with the 1 pps output from the GPS receiver under test.
- Timing Jitter measurements test equipment is needed to monitor timing KPIs
- Absolute timing error is not difficult to measure

### 3.5.5 Measurement Test Sequence for Timing Receivers

```
Set GPS condition OPEN
For each downlink frequency band (1531, 1550, 1675)
  For each (Resilient Antenna, Standard Antenna)
      MEASURE_KPI_SET()
For each uplink frequency band (1631, 1657)
  For each (Resilient Antenna, Standard Antenna)
    MEASURE_KPI_SET()
```

```
Calculate KPI averages and standard deviations for each LTE level
```

## 3.6 Cellular Device Measurements

### 3.6.1 Cellular Device Situation

Cellular devices and smart phones have rapid replacement cycles. Smart-phones are very commonly used for mapping, location, and navigation based on embedded GPS receivers as well as network provided location information. Today's best selling devices were not marketed in 2011. GLONASS capability is now included in high volume GPS chipsets and this capability may have resulted in different RF front end filter characteristics for the embedded GNSS receiver in Cellular devices.

### 3.6.2 Desired Goals

Characterize the performance of the latest, high sales volume cellular devices to update the performance baseline.

### 3.6.3 Plan

Measure only the high sales volume devices and capture and store KPI data as function of LTE signal strength.

Analysis: Use TWG defined, 3GPP-adapted test plans, which are based on measuring statistics of 2D position error. Commercial GPS simulators are very capable of supporting the 3GPP test plans.

The figure below shows the use of a cellular base station simulator to capture 3GPP KPIs.

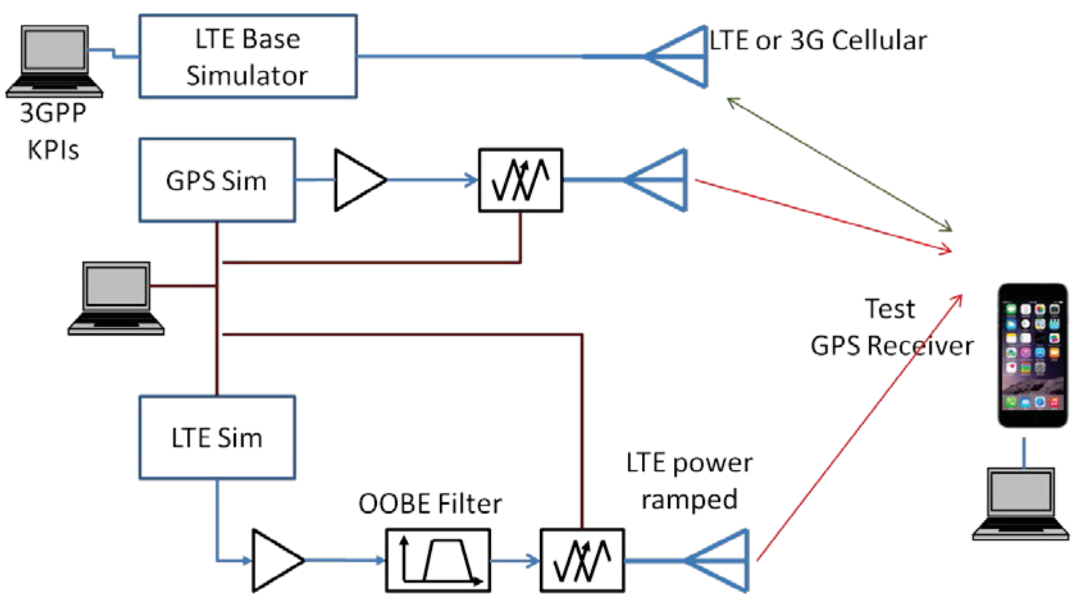



Figure 10 Cell phone KPI measurement with 3GPP base station simulator

### 3.6.4 Assumptions

GLONASS reception will not be tested but GLONASS signals may be generated depending on equipment availability.

Access to KPIs or NMEA sequences is available and exportable to an external logging system.

### 3.6.5 Measurement Sequence

A pseudo-code description of the cellular device measurement sequence is listed below.

```
For each downlink frequency band (1531, 1550, 1675)
  For each GPS condition (Open, stressed)
    MEASURE_KPI_SET()
For each uplink frequency band (1631, 1657)
  For each GPS condition (Open, stressed)
    MEASURE_KPI_SET()
Calculate KPI averages and standard deviations for each LTE level
```

## 3.7 General Navigation Device Measurements

### 3.7.1 General Navigation Situation

In prior testing, General Navigation GPS device were tested with LTE signal levels as high as -15 dBm, a level extremely unlikely to be encountered in a user scenario. The present tests will limit the maximum received power to -20 dBm.

### 3.7.2 Desired Goals

Characterize the KPI performance of the latest, high sales volume general navigation GPS devices.

### 3.7.3 Plan

Measure only the high sales volume devices and capture and store detailed KPI data as function of LTE signal strength.

### 3.7.4 Assumptions

Access to KPIs or NMEA sequences is available and exportable to an external logging system.

### 3.7.5 Measurement Sequence

A pseudo-code description of the cellular device measurement sequence is listed below.

```
For each downlink frequency band (1531, 1550, 1675)
  For each GPS condition (Open, stressed)
    MEASURE_KPI_SET()
For each uplink frequency band (1631, 1657)
  For each GPS condition (Open, stressed)
    MEASURE_KPI_SET()
Calculate KPI averages and standard deviations for each LTE level
```

# 4 TTFF AND REACQUISITION TESTING

Time to First Fix is a very important KPI for users who transition in and out of GPS coverage and simultaneously in and out of LTE coverage. For example, a public safety user exiting a building could be exposed to a strong LTE signal at the same time the GPS receiver in his two-way radio is re-acquiring GPS signals. The presence of strong adjacent band signals may increase the TTFF. TTFF is tested under cold-start and warm-start conditions which refer to how much information the GPS receiver already possesses about the satellites and the GPS system time.

The goal of TTFF testing is to determine and quantify differences in TTFF as a function of the presence of LTE adjacent band signals and the absence of these signals. The LTE signal levels will be selected to fall in a range above and below the level where significant position errors were observed. The reason for this is to conserve test time in part because TTFF may take several minutes in cold-start mode.

Re-acquisition refers to the situation where lock is lost and the GPS receiver tracking loops need to re-lock onto the GPs signal. If the outage is brief then re-acquiring satellite lock is also rapid.

To test re-acquisition the LTE signal needs to be applied at the level where loss of lock was observed.

### *4.1.1 Assumptions*

- All devices can be reset to a known cold-start state prior to each TTFF measurement.
- Access to a lock indicator is available to be able to determine when the GPS receiver has achieved lock.

### *4.1.2 TTFF Plan*

Apply LTE signals and power up the GPS receiver. Record the time until LOCK is indicated. Reset the GPS receiver and repeat N times.

Calculate average TTFF vs. LTE power for a small set of LTE powers. The figure below illustrates the TTFF measurement sequence.

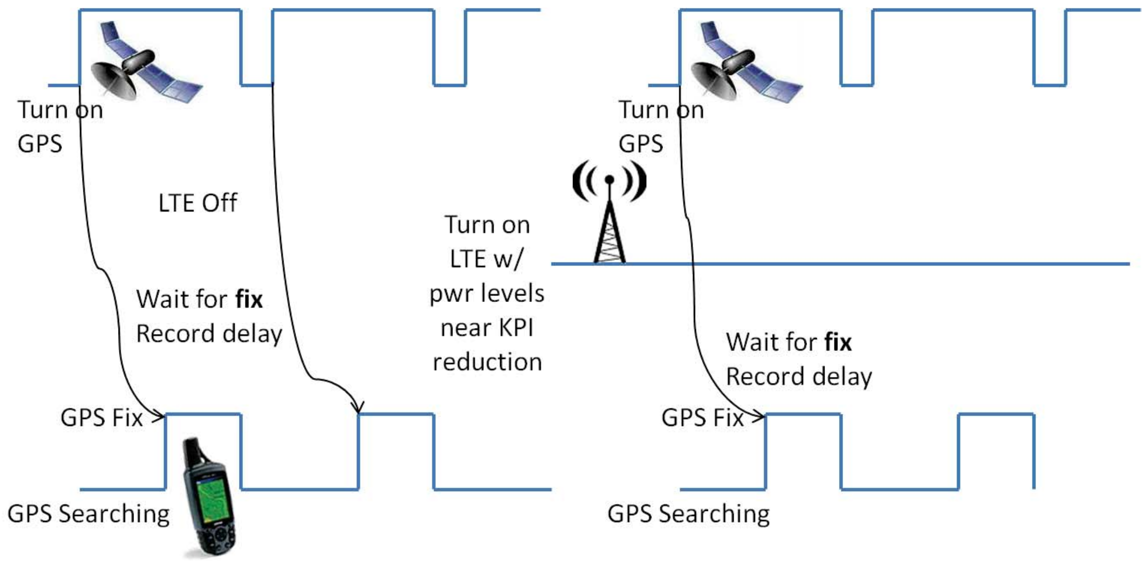



Figure 11 TTFF measurement sequence

Like position error, TTFF will also be subject to random variations from one measurement to another. For each choice of LTE power level, including no LTE signal, a set of TTFF values will be collected. These will be subjected to statistical analysis to determine KPI impact of the LTE signal.

Re-acquisition data may be available from the ramped LTE power tests used to capture position KPI data if the devices loose LOCK at the higher LTE power levels. The LTE power levels where LOCK is lost and the power level where LOCK is regained will be available.

# 5 ANALYSIS

At each LTE power level many KPI data samples will be collected. The mean and standard deviation of each KPI will be calculated for each power level sample set and logged in one of the KPI, TTFF, or Timing Test Data Tables.

Raw NMEA and other data from GPS devices will be stored in the format it is received in. It is likely that the formats will be different for each device.

Relative changes in the RMS KPI error will be the measure of interference used in later work.

## 5.1 Statistical Analysis

In order to translate the KPI vs. LTE signal level statistics collected in the measurements to a probability of harmful interference, an analysis is needed to determine the likelihood, frequency, and expected duration that a user will experience LTE levels that cause an increase in KPI standard deviation. Data is available from existing LTE networks that can be used to develop a statistical model for LTE signal levels on the ground. Scenarios can be developed for the typical movements of a user within the coverage area of an LTE network. Combining these statistics and scenarios with the KPI sensitivities to LTE signal strength will produce a picture of how often and how much the presence of the LTE network will impact users.

# 6 CHANGE HISTORY

| Version | Date | Description |
|---|---|---|
| V0.6 | June 25, 2015 | Preliminary Draft |
| V0.8 | July 22, 2015 | Added detail regarding 3GPP specific tests for cell phones<br>Updated Device List<br>Updated KPI Table<br>Updated GPS Impairments table<br>Added detail for pretest scenario: added un-impaired GPS pretest |
| V1.0 | July 27,2015 | Version 1.0 |
| V1.1 | August 24, 2015 | Updates to warm start TTFF section.  Updates to certified aviation section |
| | | |

# GPS Compatibility:
# Test Plan Summary
# August 24, 2015

# GPS and LightSquared ATC Compatibility Analysis: Overview

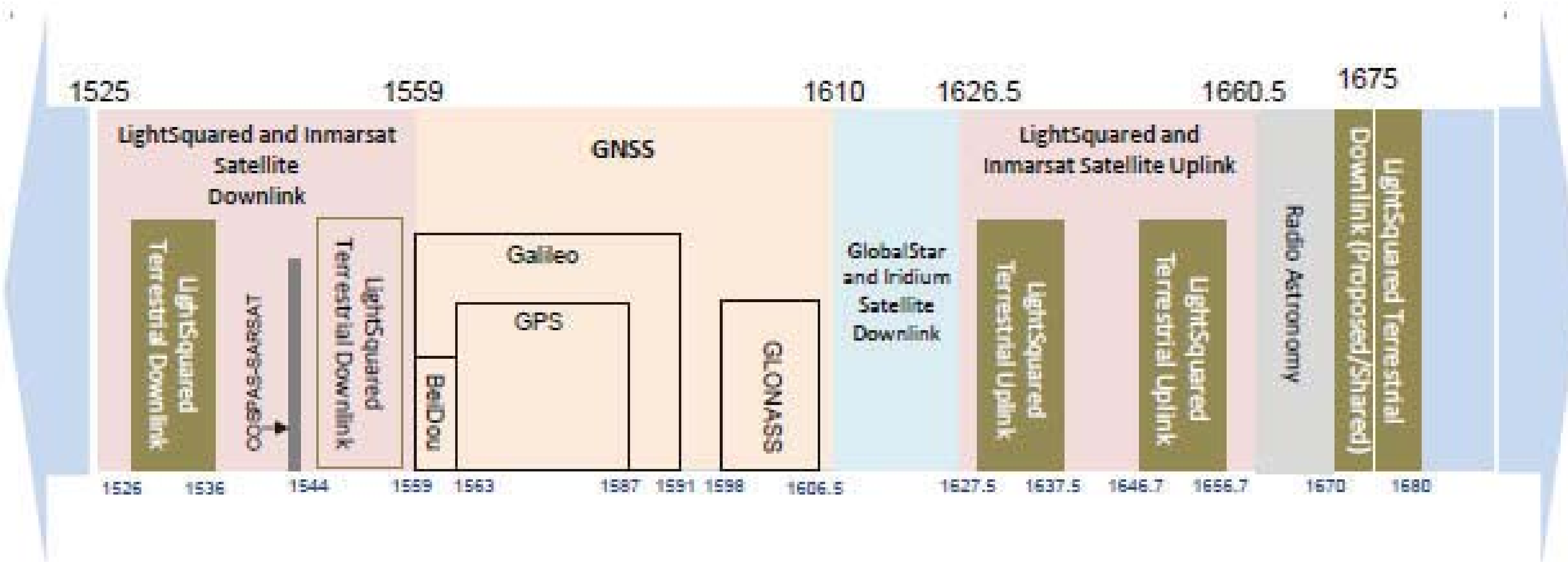


- Why Updated Compatibility Analysis is Necessary
  - Knowledge Gained from 2011 TWG
    - Understanding of GPS LTE Susceptibility and Compatibility Solutions
  - **Measure GPS receiver overload thresholds based on KPI degradation, not just 1 dB $C/N_0$**
  - Revised LightSquared LTE Deployment Plan: Frequency Bands and LTE Power
  - Progress in GPS Receiver Design

- Key Elements of 2015 Compatibility Analysis Approach
  - Radiated RF Measurements of Key GPS Devices' Susceptibility to LTE Emissions
  - Identification of LTE "Threshold of Harm" Level Based on GPS Service (User) Impact
  - Statistical Analysis of Geographic and Temporal Impact to GPS in LTE Environment
  - Identification of Characteristics of GPS Devices Compatible with LSq ATC
  - Identification of Compatibility Solutions for GPS Devices Not Currently Compatible

# GNSS Spectrum Neighborhood

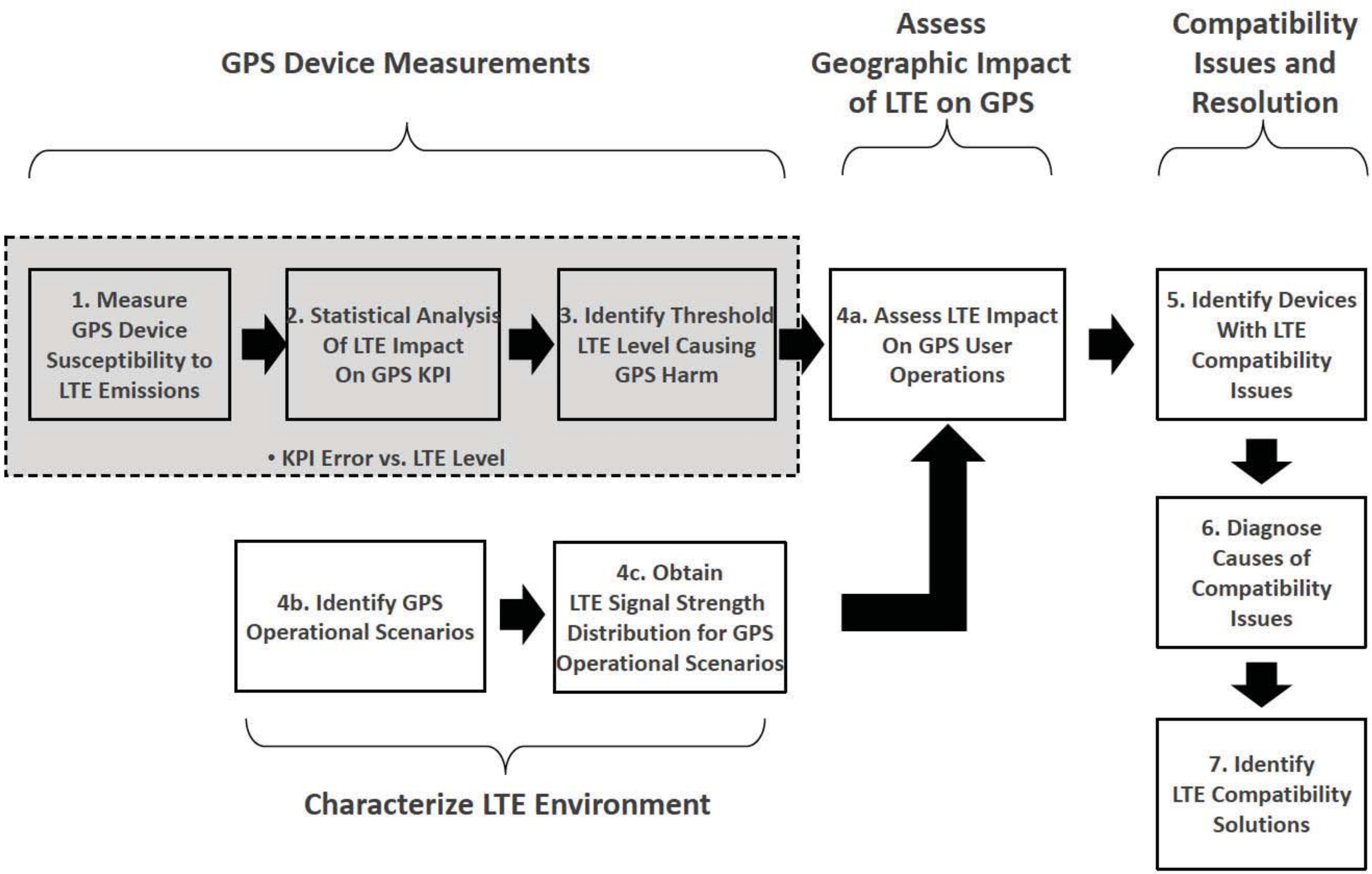





- The spectrum 1559 – 1610 MHz is allocated for GNSS service on global basis
- There are 4 major GNSS systems that share the spectrum.
- These systems use spectral separation as well as coordinated signal overlay that allow for future compatibility of devices that leverage these different GNSS constellations.
- As shown in the figure above, GLONASS signals reside closer to the LightSquared uplinks. Likewise, both BeiDou and Galileo are the lower end of the GNSS band bringing them closer to the LightSquared downlink spectrum

# Compatibility Analysis and Solution Identification Methodology





# LTE Bands and Throughput



| | Frequency Band (MHz) | LTE Throughput (simulated) | Notes |
|---|---|---|---|
| Downlink | 1526-1536 | Max. Throughput | Required |
| Downlink | 1670-1680 | Max. Throughput | Required |
| Downlink | 1545-1555 | Max. Throughput | Desirable – If Schedule Permits |
| Uplink* | 1627-1637 | ~ 3.5 Mbps (Streaming Video) | Required |
| Uplink* | 1647-1657 | ~ 3.5 Mbps (Streaming Video) | Required |

* Using actual LTE SC-FDMA uplink signals allocated among subset of resource blocks

# GPS Signal Constellations



- **For Precision Devices with Augmentation, live sky data will be used and no impairments will be added.**
- **Tests utilizing a simulator may have Impairments added up to the values in the table.**
  - **Impairments determined from "GLOBAL Positioning System Standard Positioning Service Performance Standard" 4th Edition, From GPS DIRECTORATE; Page 65 and 108.**
  - **A very conservative ZERO Age of Data is used**
  - **95% error is converted to 50% (mean) error using Circular Error Probability**
    - **(CEP50 using Rayleigh distribution with same sigma parameter)**

| | zero AOD, 95% Error | CEP50 (values used) |
|---|---|---|
| Clock Stability | 0 | 0 |
| Group Delay Stability | 3.1 | 1.4911 |
| Other Space Segment Errors | 1 | 0.481 |
| Clock/Ephemeris Estimation | 2 | 0.962 |
| Clock/Ephemeris Curve | 0.8 | 0.3848 |
| Ionospheric Delay | 9.8 - 19.6 (14.7) | 7.0707 |
| Group Delay Time | 4.5 | 2.1645 |
| Other Control Segment Errors | 1 | 0.481 |
| Tropospheric Delay | 3.9 | 1.8759 |
| Receiver Noise | 2.9 | 1.3949 |
| Multipath | 0.2 | 0.0962 |
| Other User Segment Errors | 1 | 0.481 |
| 95% System UERE | 12.7 - 21.2 (16.65) | |
| CEP50 | | 8.009047212 |

# Device List (Subject to Availability)



| Aviation (certified) |
|---|
| Garmin GTN 625 |
| Avidyne IFD 440 |
| **Aviation (non-certified)** |
| Garmin GPSMAP 696 |
| Garmin aera 510 |
| **Cellular** |
| Garmin Nuvi 2597LMT |
| Garmin Nuvi 55LM |
| TomTom VIA 1515M |
| Alpine In-Dash X008U |
| Garmin GPSMAP 76 CSx |
| Garmin eTrex H |
| Garmin Nuvi 2495LMT |
| TomTom Go 50S/60S |
| Garmin/Panasonic Uconnect 8.4N RB5 |
| Motorola APX 7000 |
| Motorola MW810 |
| Pioneer AVIC-5100NEX |
| Harman Toyota Entune 86140-02050 |
| Bosch in-dash Nissan 25915CJ0A |
| Garmin GPSMAP 78 SC |
| Garmin Montana 650t |
| Magellan Explorist 350H |
| Bushnell Onix 400 Waterproof Hiking GPS |
| Furuno GP32 |
| Wabtek Commlink II or Navigation Sensor Module |

| General location and navigation |
|---|
| Apple iPhone 5s |
| Apple iPhone 6 |
| Samsung Galaxy S5 |
| Samsung Galaxy S6 |
| iPad (w/cellular data) |
| Samsung Galaxy Tab 4G LTE |
| **High precision** |
| Deere Starfire 3000 (0907PC, 1010, 2010 and 7800) |
| NovAtel Smart6 or Smart6-L |
| Topcon SGR-1 |
| Topcon System 310 |
| Trimble AgGPS 542 |
| Trimble 5800 |
| NAVCOM SF-3050 |
| Trimble Geo 7x |
| Trimble Net R9 |
| Trimble R8 |
| Trimble TM3000 |
| Trimble SPS855 GNSS Receiver |
| Trimble SPS985 Antenna |
| Topcon HiPer AG (V) |
| **Timing** |
| Arbiter 1088B GPS Satellite Clock (40ns) |
| Symmetricom 58540A |

# Antennas

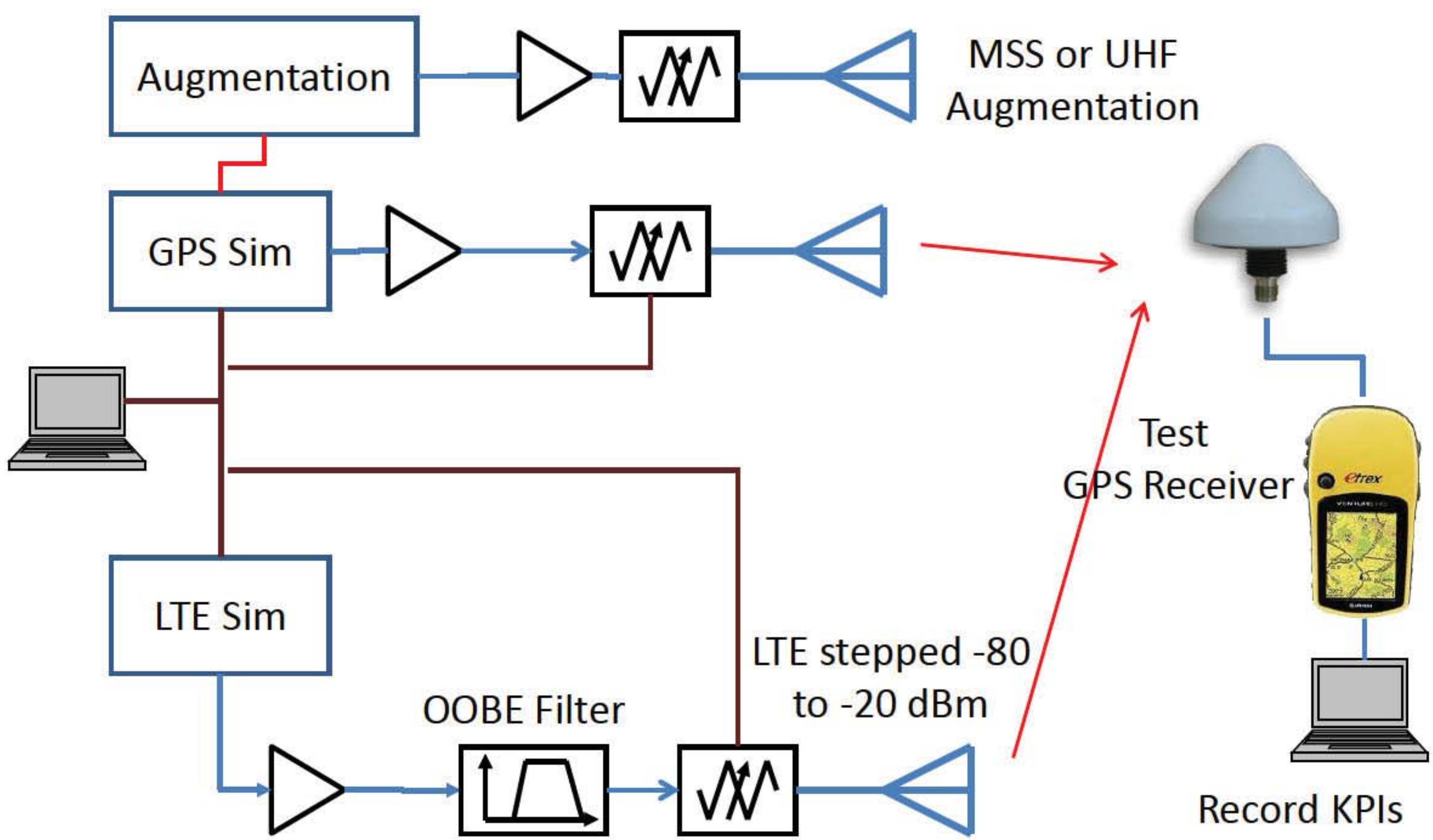


**The timing and high precision categories use external antennas.  Performance between Standard and “Interference Resilient” antennas will be compared.**

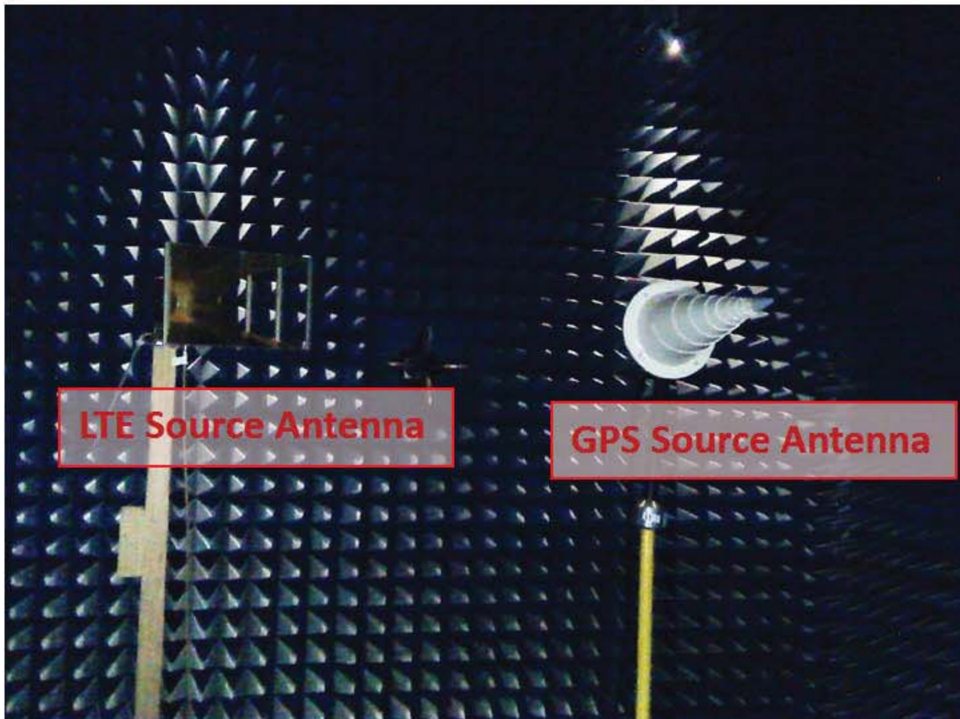
| Vendor | Class | Model |
|---|---|---|
| PCTel | Mobile | 3915D-HR |
| PCTel | Mobile | 8171D-HR |
| PCTel | Timing | GPS-TMG-HR-26N |
| AeroAntenna Technology | Aviation | AeroAntenna AT575-93 |
| Novatel | Precision / Marine | GPS-713-GGG-N |
| Javad (LSQ Provided) | High Precision | N/A |

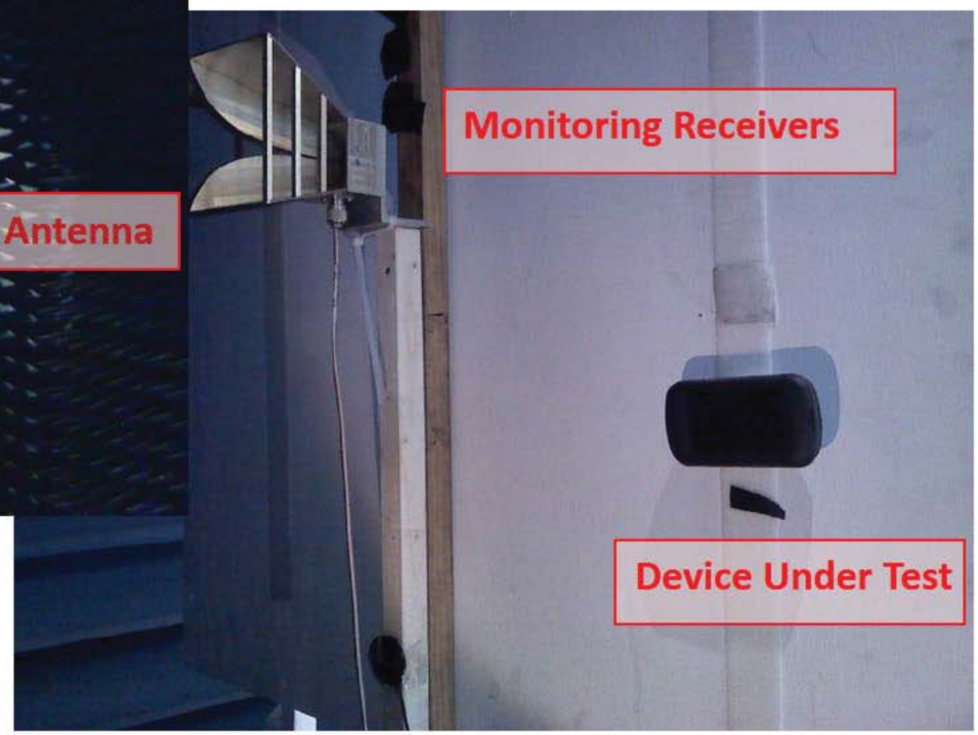
# KPI Measurement Schematic, Radiated





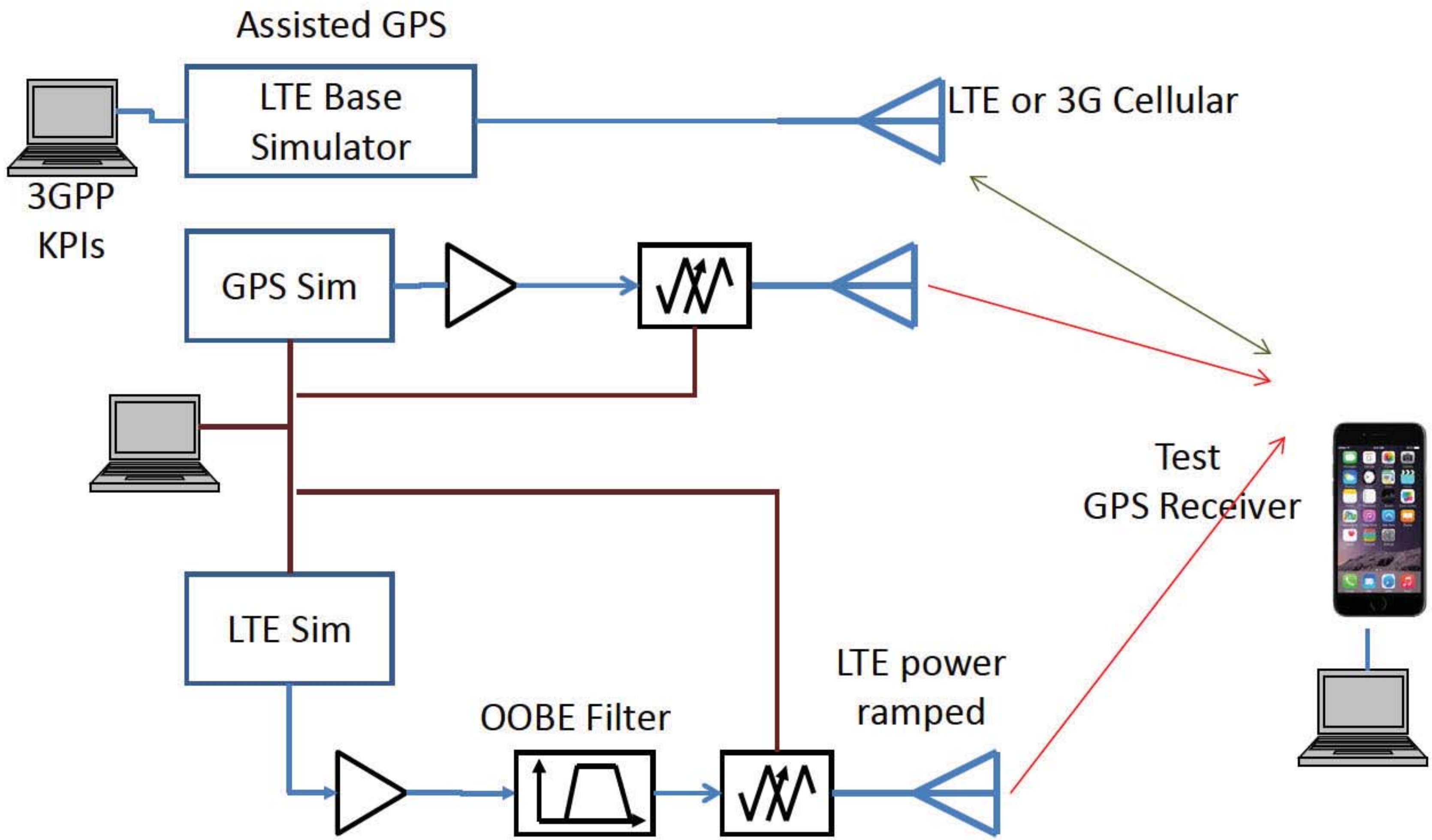
# RF Anechoic Chamber



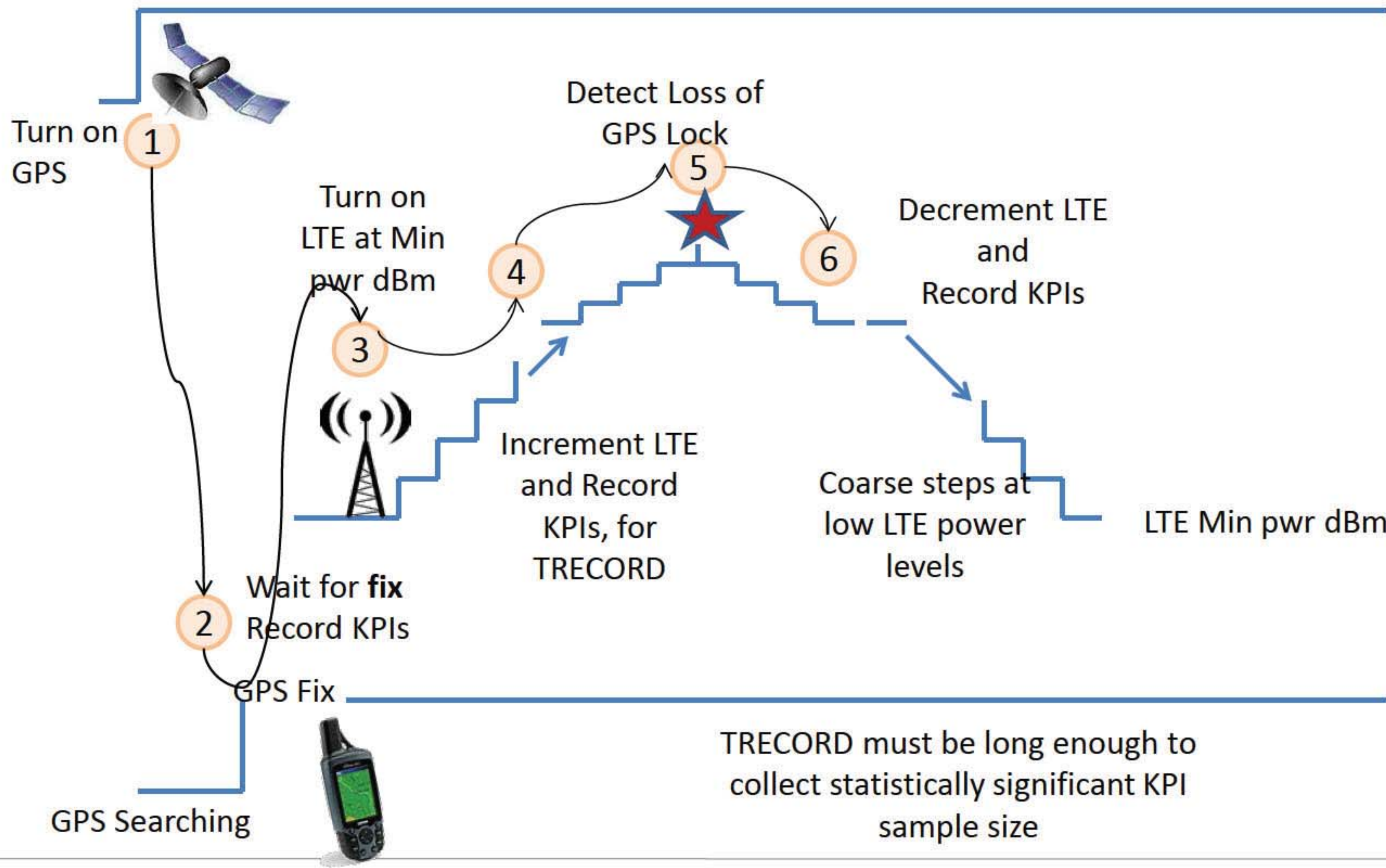
# KPI Measurement, Cell Phones





# Basic Measurement Sequence





# KPI's and System Data Recorded for Device Categories

| | Aviation (Cert) | Aviation (Uncert.) | HP (High Precision) | Timing | Cellular | General Nav |
|---|---|---|---|---|---|---|
| **KPI** | 1) 3D Position Error | 1) 3D Position Error | 1) 3D Position Error<br>2) Loss of RTK | 1) Timing Error | 1) 3GPP KPIs<br>2) 2D Position Error | 1) 2D Position Error |
| **System Data** | 1) C/No | 1) Satellites in view<br>2) C/No<br>3) DOP | 1) Augmentation Signal Quality<br>2) Satellites in View<br>3) C/No<br>4) DOP | 1) Frequency Eror<br>2) Satellites in view<br>3) C/No<br>4) DOP | 1) Satellites in View<br>2) C/No<br>3) DOP | 1) Satellites in View<br>2) C/No<br>3) DOP |

# Example 3GPP KPI from 3GPP TS 37.571-1



**Table 7.1.1.2: Requirements Sensitivity Coarse time assistance**

| Success rate | 2-D position error | Max response time |
|---|---|---|
| 95 % | 100 m | 20 s |

**Table 7.1.1.3: Parameters Sensitivity Coarse time assistance - Sub-Test 1**

| Parameters | Unit | Value |
|---|---|---|
| Number of generated satellites | - | 8 |
| HDOP Range | - | 1.1 to 1.6 |
| Propagation conditions | - | AWGN |
| GPS Coarse time assistance error range | seconds | ±2 |
| GPS L1 C/A Signal for one satellites | dBm | -142 |
| GPS L1 C/A Signal for remaining satellites | dBm | -147 |

# Individual Measurement Results and Analysis

## Test Condition [Device, GPS State, Frequency]

| Test Condition ID | LTE Level | Raw Measurements | Actual KPI Value | Measurement Analysis (Table) |
|---|---|---|---|---|
| 1 | -55 dBm | Position, C/No, SV, DOP,NMEA | 2D Pos. Error avg. + std. dev. | 2D pos. RMS error vs. C/No (LTE pwr. Level) |
| 1 | -50 dBm | Position, C/No, SV, DOP,NMEA | 2D Pos. Error avg. + std. dev. | 2D pos. RMS error vs. C/No |
| 1 | -49 dBm | Position, C/No, SV, DOP,NMEA | 2D Pos. Error avg. + std. dev. | 2D pos. RMS error vs. C/No |
| 1 | | --- | --- | --- |
| 1 | -20 dBm or loss of lock | Position, C/No, SV, DOP,NMEA | 2D Pos. Error avg. + std. dev. | 2D pos. RMS error vs. C/No |

**Identify devices exhibiting low resilience to adjacent band power for further analysis and suggested design changes.**

# GPS Compatibility with LTE: Context

# The Challenge of LTE Compatibility with GPS



**A strong adjacent channel terrestrial signal from a nearby base (LTE downlink), or nearby LTE handset (UE- user equipment), may impair the GPS receiver performance**